Asymmetric Planetary Nebulae III
ASP Conference Series, Vol. XXX, 2004
M. Meixner, J. Kastner, B. Balick and N. Soker eds.

Influence of the Interstellar Medium on the Shaping of Planetary Nebulae

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Abstract. The interaction of the ISM with the evolution of PNe is studied for cases where there is a large relative velocity between ISM and central star, for example for high-proper motion PNe. In such cases the ISM wind already interacts strongly with the AGB wind, and extensive PN asymmetries result.

1. Introduction

Stars, stellar winds, and planetary nebulae (PNe) are generally in a different velocity state than the interstellar medium (ISM) in which they are embedded. The most accurately known example is that of the Sun and its local ISM (LISM). Both the Sun and the LISM are in motion with respect to the local standard of rest; the velocities combine to a solar relative apex motion of 26 km/s.

The LISM is part of the Local Interstellar Cloud (LIC) which is warm ($\sim$ 7000 K) and dense (~ 0.2 cm^{-3} H^0, ~ 0.1 cm^{-3} H$^+$). The LIC is embedded in the Local Bubble (1.2×10^6 K, ~ 0.005 cm^{-3} H$^+$). These are but two examples of wide-ranging possible interstellar environments. Similarly, different PNe evolve embedded in a variety of ISM environments. For larger ISM ram pressures, the wind-wind interaction will naturally give rise to asymmetries in the PNe.

PNe – ISM interaction has already been studied extensively (Borkowski, Sarazin, & Soker 1990; Soker, Borkowski, & Sarazin 1991). According to recent arguments, the ISM-caused asymmetry in PNe does not only begin at an evolved stage when the thin PN shell is sufficiently diluted as to match the ISM density. Rather, the ISM already interacts with the AGB wind of the central star and

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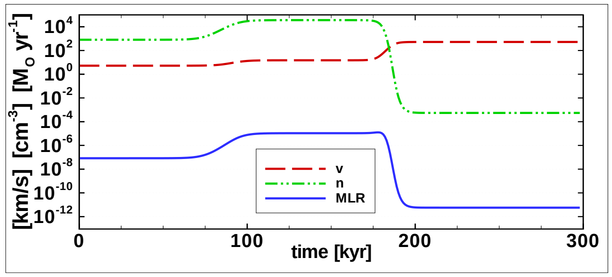

Figure 1. Assumed, simplified history of the evolution of the CS. The composite plot shows the wind velocity (dashed, in km/s), the density at 0.01 pc (dot-dashed, in cm^{-3}), and the mass loss rate (MLR) of the wind (solid, in $M_\odot$ yr^{-1}), versus time in kyr.

can shape the region of the circumstellar material, and the proto-planetary nebula (Villaver, García-Segura, & Manchado 2002a, 2003; Villaver, Manchado, & García-Segura 2002b). This contribution seeks to extend the published work to high-velocity regimes which are probably responsible for the structure of high-proper motion PNe such as the PN around Sh 2-68 (PN G030.6+06.2; e.g. Kerber et al. 2002). Sh 2-68 has a large proper motion, and is off the geometric center of a 15' core nebula. There is an extended tail, that extends over $\sim$ 30' (see figure in Kerber et al. 2003). Both these facts suggest an ISM flow interacting with the stellar outflow beginning early on in the star's evolution.

2. Simple Model of Time-Dependent AGB/post-AGB Stellar Wind

We model the wind-wind interaction from the onset of the AGB wind to the evolved PN in an axisymmetric configuration, with the symmetry axis containing the ISM flow vector and the CS. We use a simplified 2D hydrodynamic numerical model (magnetic fields are neglected) based on the Zeus3D package, with radial distance from CS and angle from the symmetry axis as coordinates. The numerical region is bounded by the inner (stellar wind) boundary at r = 0.01 pc (2000 AU) and the outer (ISM) boundary at r = 16 pc, and is realized on a 430 $\times$ 37 grid. The stellar wind evolution is modeled in an approximate, simplified way. Initially, the grid is filled with a uniform ISM. At t = 0, a slow AGB wind starts, with a mass loss rate (MLR) of $\dot{M} = 8 \times 10^{-8} M_\odot$ yr^{-1} and terminal wind velocity of 7 km/s. Figure 1 shows wind velocity, wind density at 0.01 pc, and mass loss rate in a combined plot. At 66,000 years, a transition to the thermal pulse regime starts, reached at about 100 kyr. The AGB-TP regime is characterized by $\dot{M} = 10^{-5} M_\odot$ yr^{-1} and a terminal wind velocity of 15 km/s; see Figure 1. After 80 kyr in the TP phase, the wind transits to the post-AGB phase with $\dot{M} = 6 \times 10^{-12} M_\odot$ yr^{-1} and $v = 520$ km/s. The values for a given CS can be expected to substantially differ from this assumed model history; the allowed ranges for the velocity and MLR are likely very broad.

We conduct a limited parameter survey and study six different ISM environments, all at 8000 K: Two relative ISM velocities, 64 km/s and 104 km/s, and three ISM hydrogen densities: 0.2, 0.1, and 0.02 cm^{-3}.

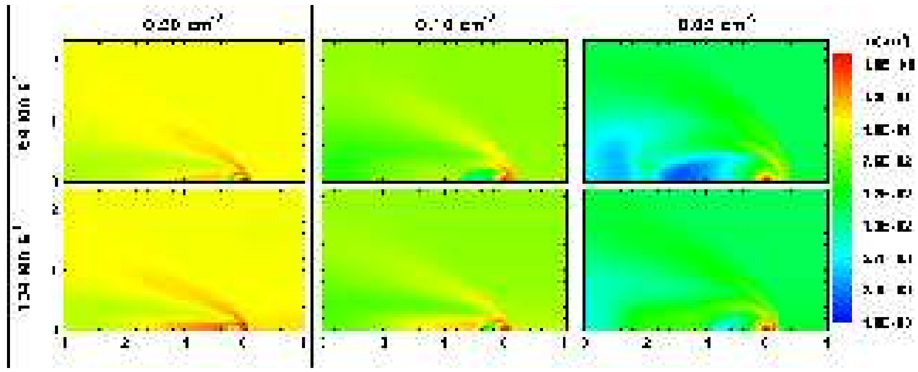

Figure 2. Snapshot, at 66 kyr, of the evolved quiet-time AGB wind interacting with the ISM. The CS is at (0, 0), and the ISM wind enters from the right. Color-coded number density maps are shown for all six models. All distances in parsec.

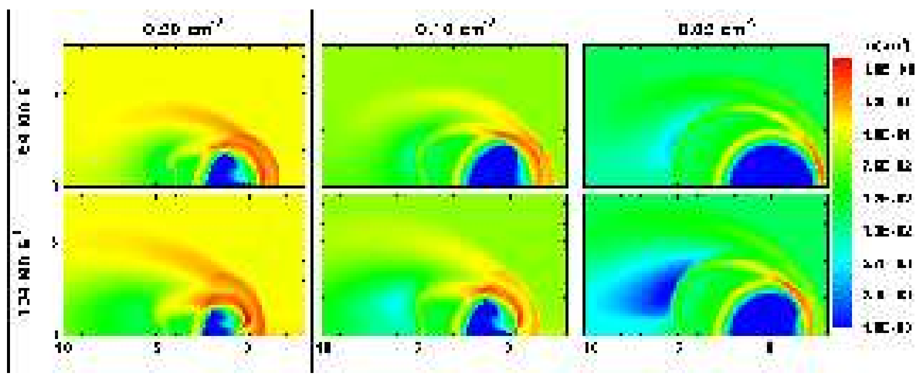

Figure 3. Color maps of number density, for all six models, at 220 kyr, soon after the post-AGB wind has reached the dense structures.

3. Results

Right from the start of the modeled evolution, the ISM interacts with the emerging AGB wind and distorts the evolution, creating asymmetry. This is the case even for the smallest ISM density of 0.02 cm^{-3}. Figure 2 shows the two-dimensional density distributions after 66 kyr of such an evolution, for all six models. The snapshot occurred just before the gradual onset of the TP phase. The ISM/CS wind-wind interaction is obvious. In all cases there is an overdensity and compression in the nose direction and a density depletion in the tail region. The interaction manages to divert material into the post-tail region (downwind), creating another overdensity. The different interstellar ram pressures in the six models give rise to different opening angles of the overdense structures, and to different distances where these structures cross the stagnation axis.

The dense stellar wind of the AGB thermal pulse cannot restore symmetry, even when this phase is rather long as it is in our evolution model. The increased

density and velocity of the AGB-TP wind shifts the pressure balance and lets the existing structures grow in size. This growth has not ended when it is overtaken by the initial blast of the post-AGB wind. Figure 3 shows the density distribution relatively soon after the white dwarf wind has reached the dense structures, at 220 kyr. The wave compresses the structures, and empties a large interior region. The post-AGB wind upsets the balance through a decreased ram pressure which allows the ISM ram pressure to diffuse some of the dense nose material towards the CS, in some cases even drilling a hole at the nose.

When tracked further, the interaction will separate the CS from the PN for the larger ISM ram pressures. The general expansion of the nebula dilutes it, and the ISM wind ablates it further.

4. Conclusions

If the ISM is anything but very tenuous, the sellar wind of an AGB-branch star will interact with it. As a minimal consequence, present even for modest ISM ram pressures, the ISM will take emerging structures like PN shells downwind and hence the CS will be off the geometric center of the nebula.

For the ISM parameters studied, non-spherical structures develop already in the AGB phase. Spherical symmetry is never regained. We have run the exact same stellar evolution (stellar wind history) for six different ISM environments. The modest variation of ISM ram pressure by a factor of 200 resulted in vastly different AGB end states and PNe.

In particular for high-proper motion PNe, the wind-ISM interaction hence needs to be taken into account. For a realistic model that places constraints on PNe and the CS from observations, a realistic mass loss history is needed, expanding on the toy model presented here (Figure 1). Villaver et al. (2002a,b, 2003) use many such realistic ingredients, including wind evolution derived from stellar evolution, photoionization, radiative cooling, etc. Even more physics is likely needed for a realistic model, such as stellar and interstellar magnetic fields, stellar rotation, and the ionization state of the ISM.

Acknowledgments. HRM gratefully acknowledges NASA grants NAG5-12628 to the University of Delaware and NAG5-13611 to Dartmouth College.

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